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DERIVATION OF MAINTAINABILITY REQUIREMENTS FOR MILITARY WEAPONS SYSTEMS

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DERIVATION OF MAINTAINABILITY REQUIREMENTS FOR MILITARY WEAPONS SYSTEMS

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INTRODUCTION

The year 1962 has brought a significant change to the way in which the military customer has specified maintainability (M) requirements in his contracts.

In the past, maintainability and maintenance requirements, if mentioned at all, were generally called out as a best effort item. No criteria were specified to establish even a minimum base for this best effort work. Contractors were free to interpret the contract requirement in any manner they chose. Since a rigid interpretation generally meant time and money, and since they could always be sure that at least some of their competitors would be less conscientious than themselves about this innocuous requirement, it was generally easier to agree to best effort and let it go at that. Doing otherwise often priced them out of the competition.

Action by DOD* and the military services culminated in a number of maintainability specifications in 1962 and drastically changed this earlier approach to the maintenance problem. Each service will publish quantitative requirements for maintainability. The objective of these requirements is to insure that M is considered as a design parameter and that M considerations are factored into future systems development programs along with the traditional considerations of engineering performance and (more recently) reliability. Common points of these requirements are as follows:

1. They are specified in quantitative terms, and hence should be capable of being predicted in advance, measured and evaluated during equipment development, and subsequently demonstrated.

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* Department of Defense directive 3200.6 of June 7, 1962 outlines the reliability and maintainability information required in future Requirements Documents and Technical Development Plans.

2. They are derived from (and bear direct relationship to) the mission requirements of the specific system, and

3. They require well organized, well planned, and well implemented programs, on the part of both the customer and the contractor if the stated quantitative requirements are to be met.

One basic criterion present in all of these specifications is "time". It has finally been officially recognized, for example, that the "downtime" or turn-around time criterion is an important element in the ability of a system to accomplish its mission. Further, this particular criterion is a fundamental measure of the effectiveness of the maintenance action, since it can be combined with other maintenance data such as cost, effort and resources to provide appropriate indices of maintenance efficiency. Downtime is the most direct link between system effectiveness and maintenance action; it is not, of course, the sole measure of the efficiency of the maintenance action.

CURRENT M SPECIFICATIONS

Examples of this M criterion as defined in four important military specifications are as follows:

1. MIL-M-26512-B(USAF) Maintainability Requirements for Aerospace Systems and Equipment (paragraph 6.3.1).

"6.3.1 Maintainability - The combined qualitative and quantitative characteristics of materiel design and installation which enables the accomplishment of operational objectives with minimum expenditures including manpower, personnel skill, test equipment, technical data, and facilities under operational environmental conditions in which scheduled and unscheduled maintenance will be performed. Maintainability is effective at all levels of maintenance as follows:

"a. Maintainability (organizational) - The capability of an equipment to be returned to an operational status in a specified period of time.

"b. Maintainability (field) - The capability of an equipment to be returned to a serviceable status with specified test and repair equipment within a specified period of time.*

"c. Maintainability (depot) - The capability of an equipment to be overhauled and returned to a serviceable condition at a specified percent of unit cost."

2. MIL-M-23313 (BuShips) Maintainability Requirements for Shipboard and Shore Electronics Equipment and Systems.

"3.2 Maintainability requirements - The procuring activity will specify an equipment repair time (ERT) in the detailed equipment or systems specification. The design of the equipment or system shall be such that the geometric mean of all active repair time intervals required to repair independent failures shall not exceed the specified ERT. Compliance with this requirement will be verified in the final design stage, and in the preproduction and production stages . . . "

3. XWR-30 (BuWeapons) Weapons Readiness Achievement Program, Part III, Section I, page 10 (Maintainability Requirements).

"Mission requirements, such as availability or permissible $\bar{M}$ (average) and M (maximum) downtime of the end article per specified period shall be the basic criteria for the proposed maintainability philosophy. The quantitative requirements for maintainability shall be expressed and measured in terms of mean ($\bar{M}$) and maximum (M_{max}) system or equipment downtime . . . "

4. SCC-4301B (Army) Maintainability Design, paragraph 3.2.1, Maintainability Definition.

" . . . maintainability is defined quantitatively in relationship to its relative effect in each of five consequence areas: Downtime, maintenance time, logistics requirements, equipment damage and personnel injury."

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* Note that downtime requirements are not in themselves sufficient—man hours effort, cost, and resource utilization are also necessary considerations in any maintainability analysis program.

DERIVATION OF PREFERRED SYSTEM REQUIREMENTS

With this background we can now describe how maintainability requirements may be derived from the mission of the system and how one M characteristic is related to other system characteristics.

As a starting point, Figure 1 demonstrates the logical steps in delineating preferred system requirements. Reading from the top of Figure 1, general operational requirements establish the context for a spectrum of missions which take into account environmental and geopolitical considerations as well as economic and technical limitations (for example, anti-ICBM defense, antisubmarine warfare). A specific mission, e.g., antisubmarine warfare, can then be translated into its specific operational requirements through appropriate studies. At this point functional mission requirements can be derived. Force structure analyses and cost-effectiveness studies then permit selection of the preferred system (say, killer submarines for the ASW example) from an array of synthesized alternatives which presumably meet these functional mission requirements.

In the past, the "preferred" system has most often been defined directly by the military customer, sometimes without exploratory studies to evaluate alternatives. The present trend, however, is toward broad cost-effectiveness analyses of alternative system configurations, taking into account the full operational life of the equipment and total force requirements, prior to developing hardware specifications for a specific system.

Figure 2 presents a context for considering maintainability requirements within the framework of the total weapons system. (Reference 1 describes this context and an appropriate model in more detail.) Once a preferred system has been specified, it is possible to derive quantitative requirements for it in terms of performance and operational availability, considering specific mission requirements and the given constraints (e.g., technological limitations, time, resource limitations, cost). Tradeoff studies between performance and operational availability are prerequisites to establishing intelligent requirements for these factors.[2, 3] After operational availability goals are established, appropriate quantitative requirements for system reliability and maintainability can be developed through further tradeoff studies.[4] These requirements

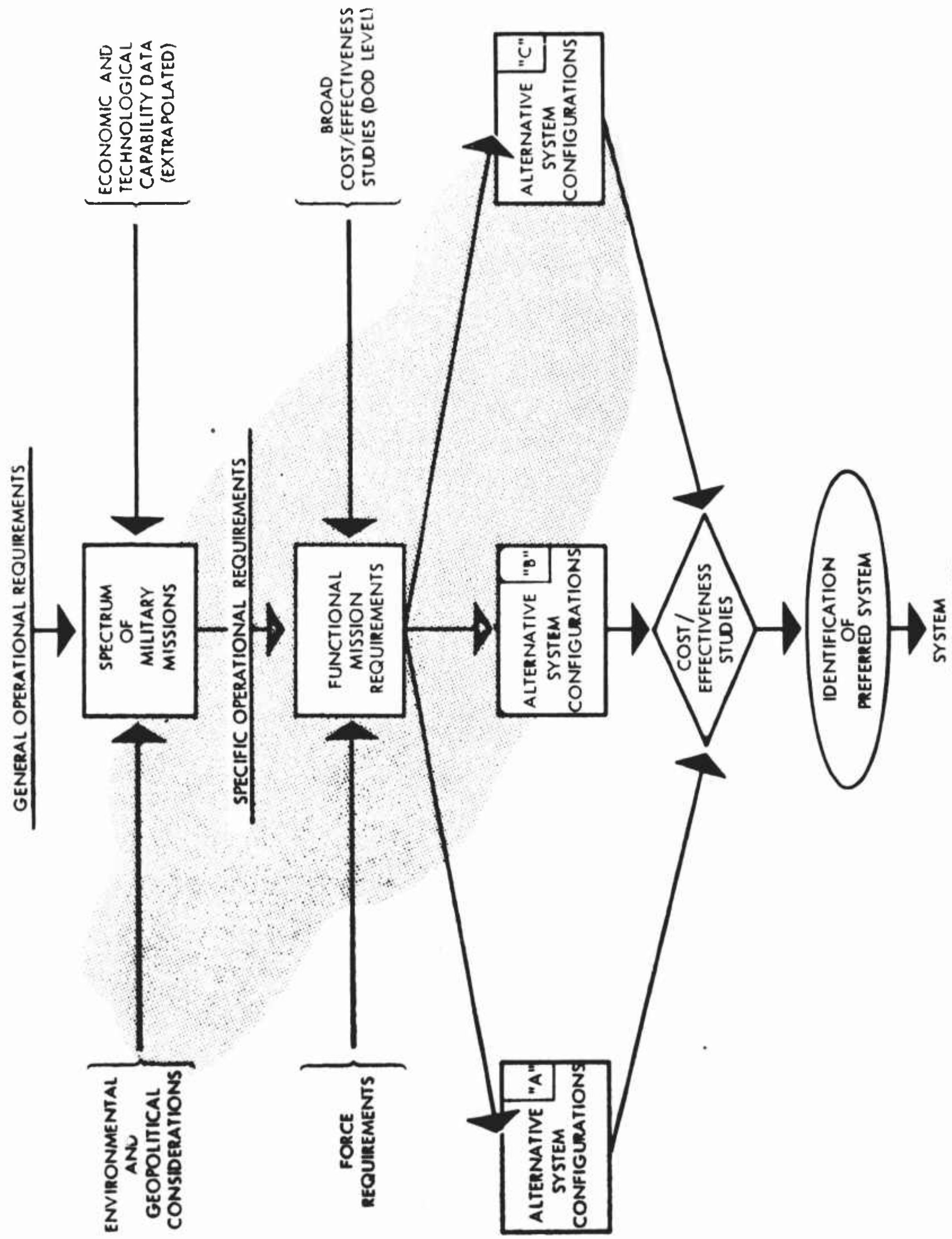

Figure 1. Derivation of Military System Maintainability Requirements 03916 U

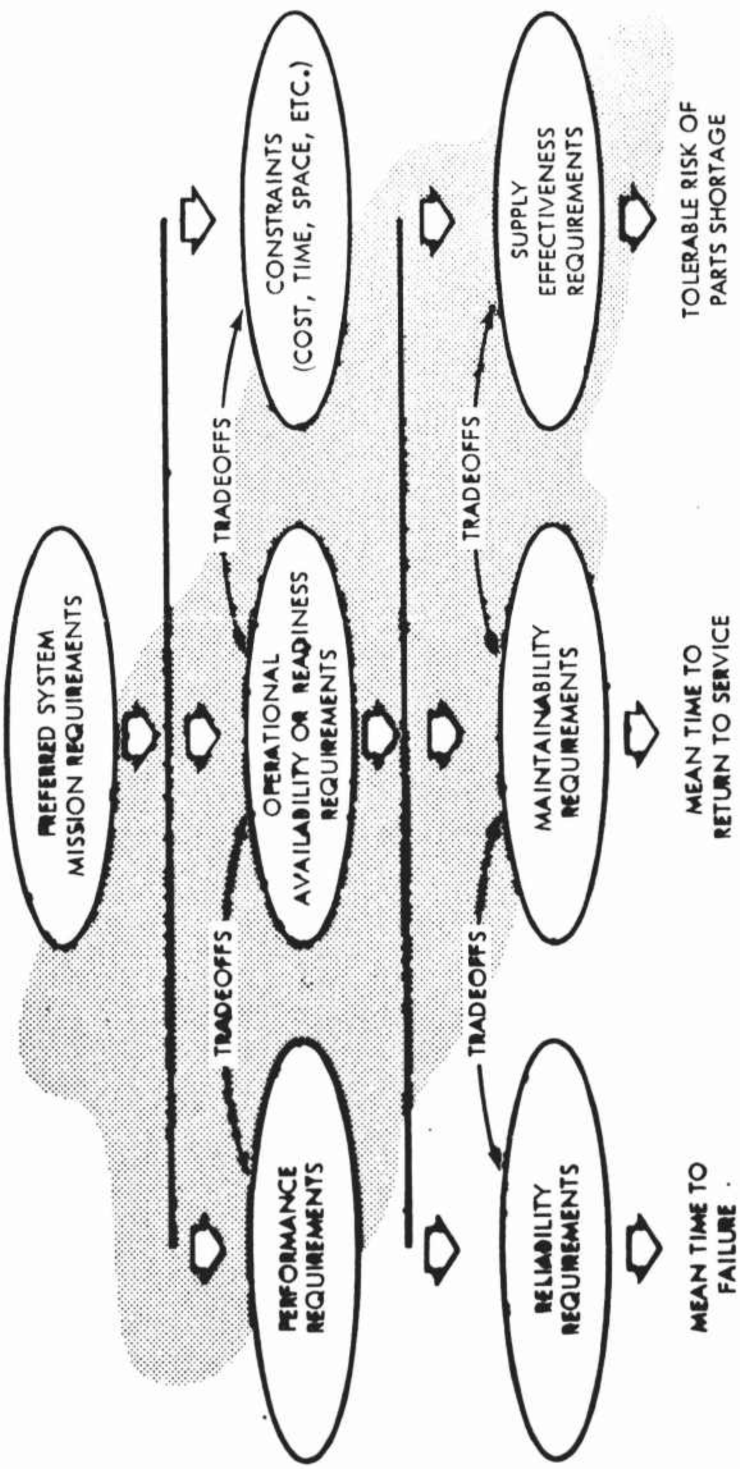

Figure 2. Derivation of System Operational Requirements 03918 U

can then be allocated from system to subsystem to component as explicit design objectives. This process is the basis for translating mission requirements into detailed M design criteria.

DERIVATION OF M REQUIREMENTS

Figure 3 presents a graphic interpretation of a mission profile for a hypothetical missile fire control system.

For any such system (and generally for its independent functional subsystems) a "demand" profile (or family of profiles) can be derived from mission requirements. Depending on the specific mission, certain limitations exist on the operational availability per mission cycle; on the maximum number of failures per mission cycle; and on the maximum tolerable downtime per failure. If these limitations are not exceeded, the system will meet mission requirements; if they are exceeded, it will not.

Figure 4 shows, graphically, how to convert operational availability requirements to specific R and M requirements within mission constraints. Many combinations of R and M requirements can be obtained for a given availability level. For example, a 90 percent availability level can be attained through a failure rate of two failures per mission-cycle and a corresponding downtime of 60 minutes per failure instance. The same 90 percent availability can also be attained by a failure rate of ten failures per mission cycle and a downtime of 12 minutes per failure. If both of these alternatives are tolerable for the mission, the system manufacturer should have that much latitude in meeting the availability specification. For example, the manufacturer may have special talent in the development of automatic test or troubleshooting equipment and hence could meet the specification more economically by reducing downtime rather than improving reliability. Total costs should be investigated prior to such a decision, of course, since reliability improvement is a one-time R&D cost that can mean savings in maintenance costs over the entire program length.* Cost tradeoff studies, therefore, between reliability and maintainability requirements are necessary before deriving final M requirements.[4]

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* Note that these savings represent at least the minimum dollar amount that can be justified for investment in R&D reliability improvement programs.

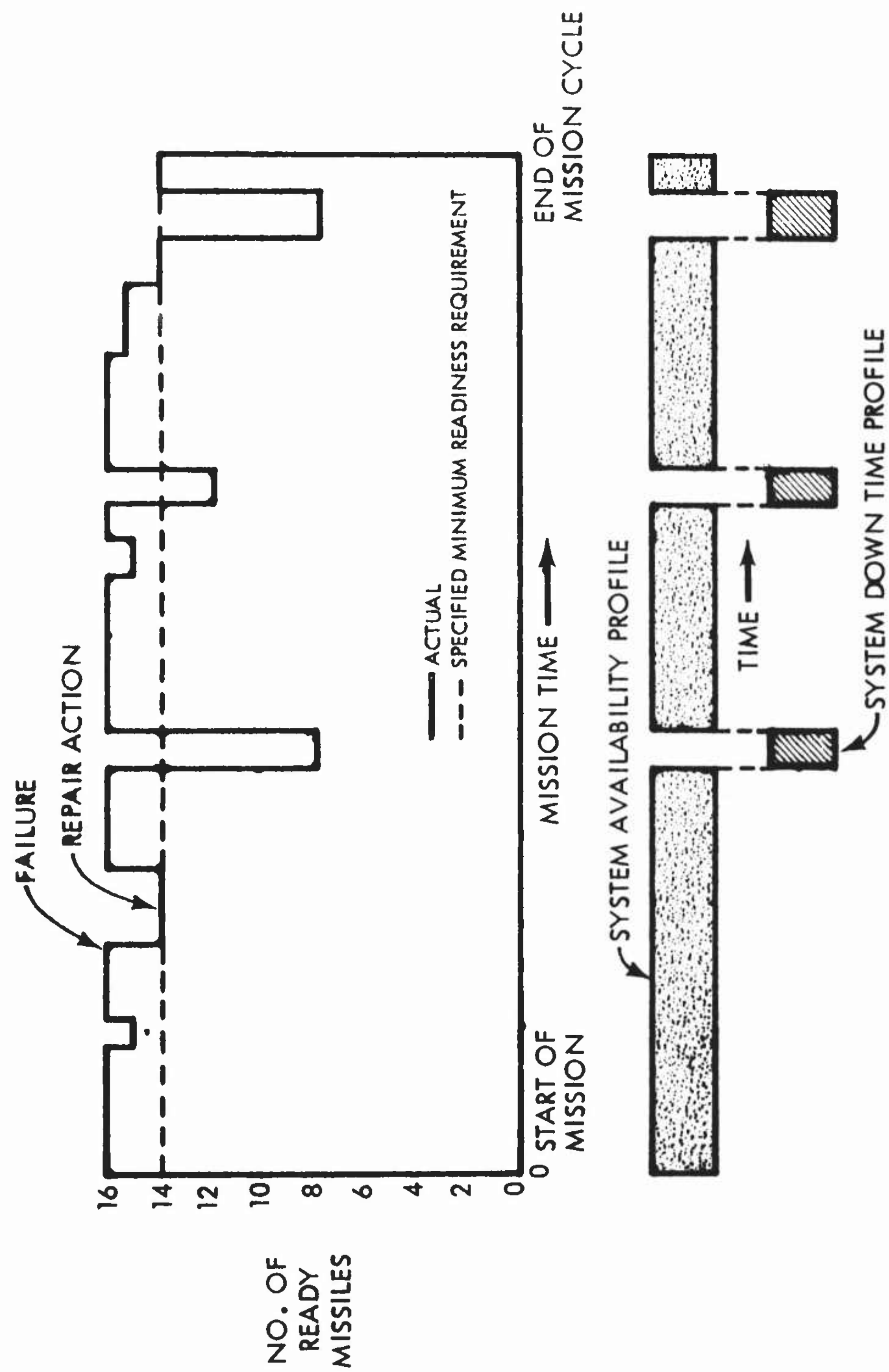

Figure 3. Mission Profile for Hypothetical Missile Squadron 03919 U

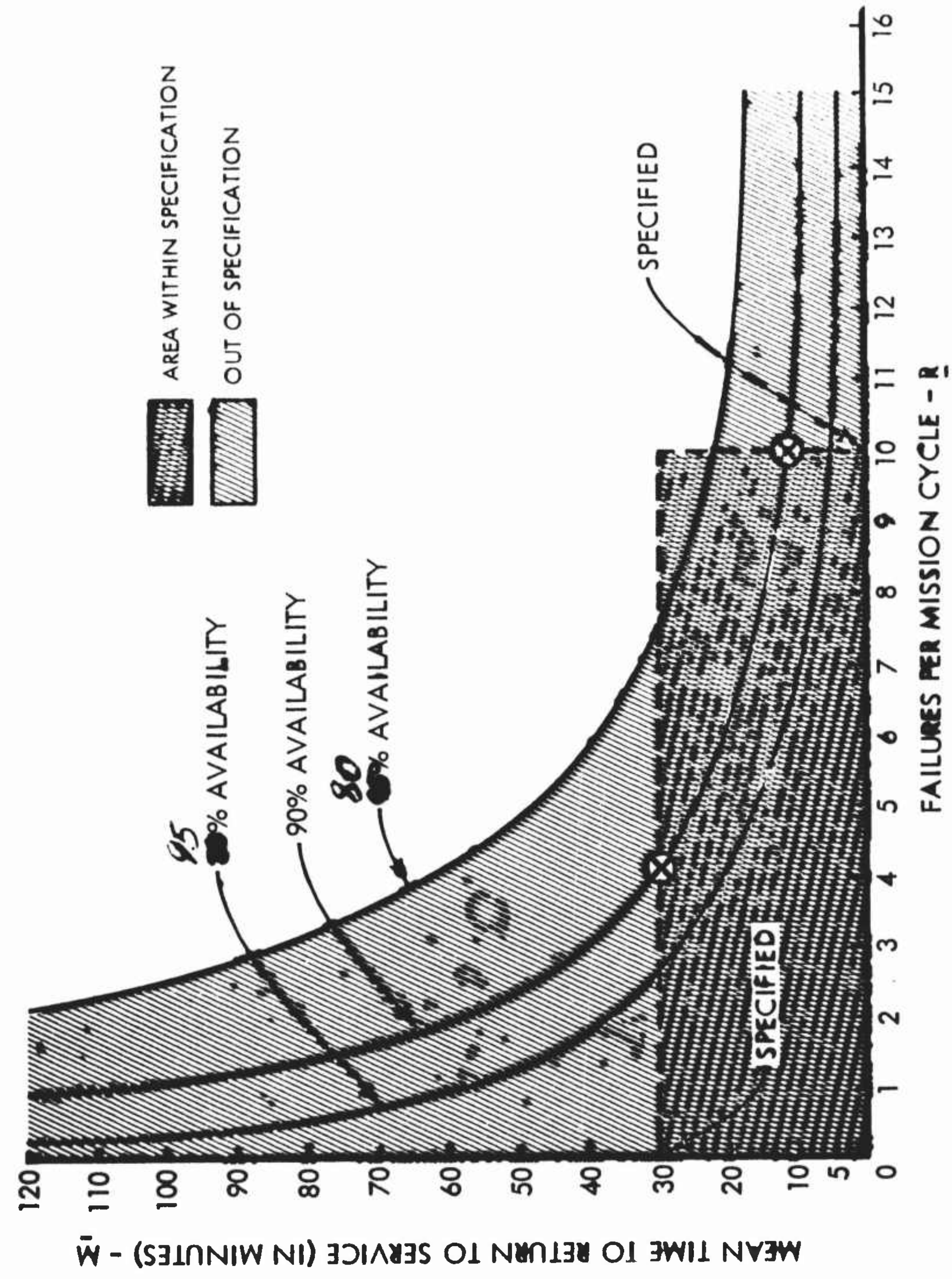

Figure 4. R Versus M Tradeoffs

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Once such tradeoffs are made, R and M requirements for a system can be spelled out as shown in Table 1. This table shows how the three factors of operational availability, reliability and maintainability might be specified for our hypothetical fire control system:

Table 1. Hypothetical Requirements Allocation

Specifications	Required Performance Level	System Operational Requirements Factors			Base Time Period
		Avail.	Reli.	Maint.	
1	Max. Level	$\geq \underline{Am}$	—	—	$\geq T_m$
2	Max. Level	$\underline{A_1}$	No. of non-consecutive failures $\leq N_1$	Downtime per failure $\leq \Delta t_1$	1 day

Specification 1. This specifies average operational availability ($\underline{Am}$) of the system for the prescribed mission and performance level (e.g., 14 ready missiles). If a large number of missions were made we would expect the attained average operational availability to be close to this number.

This particular specification does not, however, take into account nor restrict the fluctuations about the expected value of $\underline{Am}$ which which would occur on individual missions. Further, as previously noted it does not impose a limit on tolerable failures per unit time (per day in our example) or on tolerable downtime per failure. An additional specification (such as No. 2) must be used if mission analyses have indicated the need for these restrictions.

Specification 2. This limits the fluctuations we would expect about the average $\underline{Am}$ noted in Specification 1 and imposes additional R and M requirements as derived from mission analyses. This specification can be interpreted to state that the system shall be able to remain at the specified maximum performance level for not less than $\underline{A_1}$ (where $\underline{A_1}$ is specified availability per unit time—day). It further states that there can be no more than N_1 nonconsecutive failures per day (failure defined as less than specified maximum performance) and the downtime per failure cannot exceed Δt_1. Here we introduce R and M requirements for the first time.

These specifications state that the specified performances shall be met. This can be interpreted to mean that the probability that they are not met on a particular mission is to be negligible, say less than one percent. The acceptable risk of not meeting requirements on a particular mission must be spelled out in order to predict and verify whether the system involved meets its operational requirements.

Summarizing, requirements for system operational availability (including its components of reliability and maintainability) should consist of at least the following for each discrete performance level:

1. The specified average operational availability per mission cycle.

2. The specified minimum operational availability per unit time (when appropriate).

3. A specified maximum tolerable failure rate per unit time or per mission cycle.

4. A specified maximum tolerable return to service rate per failure.

5. A minimum acceptable probability that the specified limits will be exceeded in any single time base.

Whether or not a system will meet such requirements can only be verified by a well planned demonstration program. Such a program should be an integral part of the overall project and should be designed to accept or reject the hypothesis that the system meets requirements.* The Air Force, as noted, is currently working on requirements for such a demonstration program.

DISTRIBUTION OF DOWNTIME

The total length of time that a system is down for maintenance, of course, varies statistically from one failure to another. Further, it also varies for repetition of a given failure type and the corresponding repair cycle.

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* Such a program, of course, would be to evaluate both the intrinsic (designed in) capability and the extrinsic (such as those influenced by human factors and the operating environment) aspects of the system in question.

Analysis of experimental data on system downtimes shows that the observed range of variables can be fitted in most cases by a log-normal distribution.[5] The lognormal is a distribution in which the logarithm of the distributed variable is normally distributed. Technical details of the parameters involved and the rationale behind this distribution's applicability are contained in the above referenced report.

The importance of the existence of an appropriate statistical distribution to describe downtime variations to the designer and the M engineer should not be overlooked. It provides a mechanism for definitively assigning downtime requirements to subsystems and components. For example, a mean or expected value can be specified for downtime, plus a "rider" that no more than a fixed small percent of repair actions should exceed some predetermined larger value of downtime.

Technician error rate is a key variable in such a specification, since it represents the combined effects of technician experience, training, aptitudes, and prescribed procedures. In fact it is possible that research will show that the error rate has a strong bearing in the determination of the most appropriate downtime distribution, thus resolving a current controversy between proponents of the lognormal on the one hand and the exponential on the other.

It also appears reasonable that technician error rate, at some future time, can be made as explicit a system's requirement as downtime. Considerable research will be necessary, however, to correlate error rate with factors such as design requirements and technician proficiencies. Psychological problems in obtaining accurate data on this factor are also recognized.

To return to our basic thesis—Figure 5 schematically breaks the downtime requirement for our example—a typical modularized fire control system, into its basic functional elements such as detection, diagnosis, correction and check. In order to meet system requirements, downtime goals must be allocated at least to these functional elements at the system, subsystem and module levels.

At present, insufficient data exist on most operational systems to determine the contribution to downtime of these basic elements. Further, for developmental systems, techniques are just beginning to evolve which will permit prediction, from the design configuration,

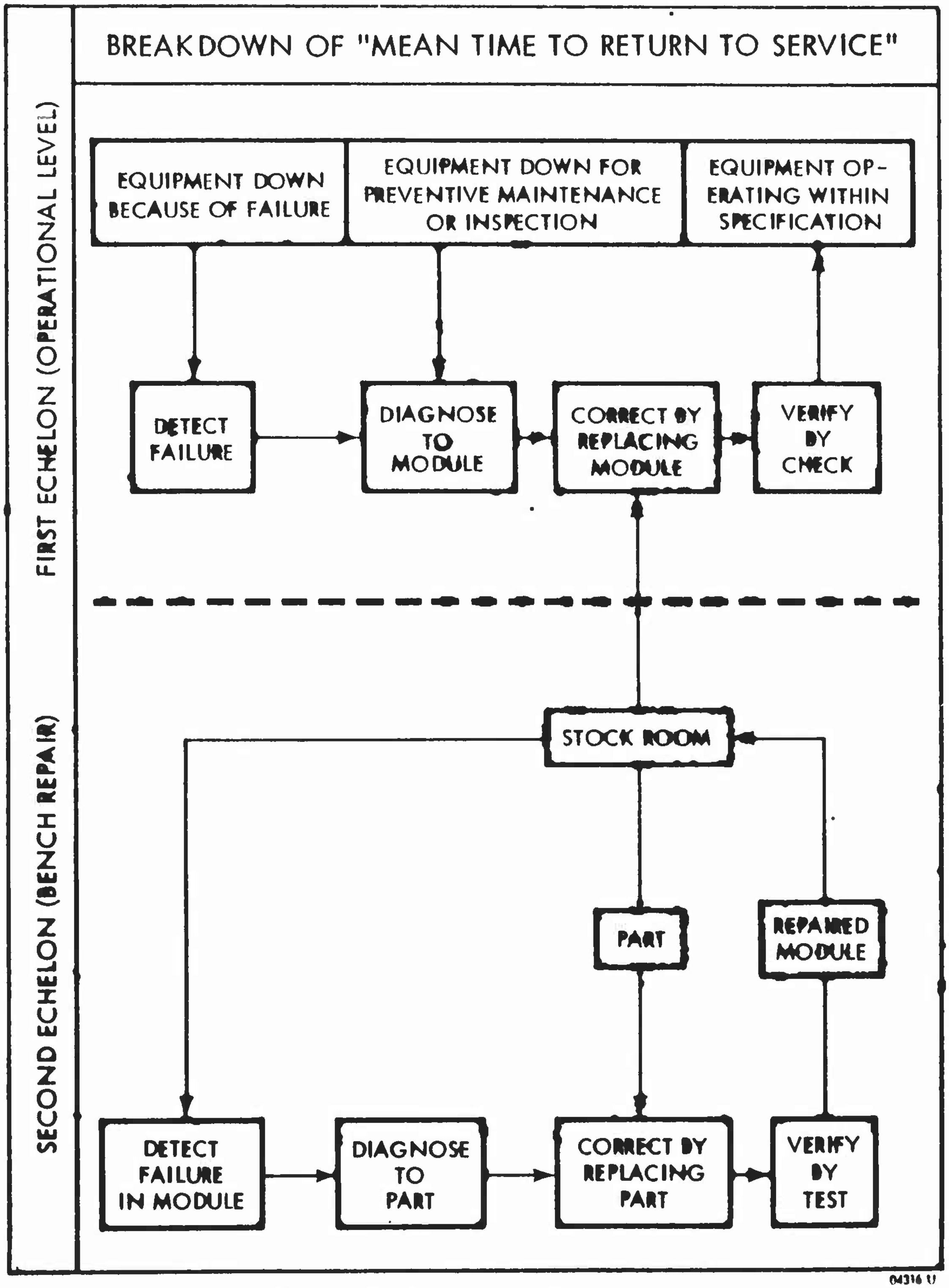

Figure 5. Elements of Downtime

of the expected contribution of each of these elements to total downtime.[6]

The ability to predict these elements of downtime at the design stage is fundamental if maintainability is to become a quantitative design parameter. Reliability was at a comparable stage of development about a decade ago. It required considerable research, planning and testing, plus data gathering and analysis, to reach the present stage wherein component and system reliability can be predicted within satisfactory accuracy at the design stage. Maintainability can move more rapidly to a similar level by drawing on experience and techniques from the reliability engineering field. The fundamental need, of course, is derivation of predictive data through properly planned and controlled programs. Requirements are meaningless to the design engineer unless there are predictive methods available to assist him in designing to meet them. Knowledge of the accuracy of these methods is, of course, also a prerequisite.

It is a two-pronged problem—the need, on the one hand, to state requirements quantitatively and explicitly and to allocate them to specific functional equipment groupings the designer works with—the need, on the other hand, to be able to predict, at the design stage, the capability of these functional groups to meet the imposed requirements.

SPECIFICS OF MAINTAINABILITY

We have now reached the point where we have developed quantitative "downtime" or "return to service" requirements for our hypothetical system. These requirements have been derived from the customers stated equipment mission and have been evaluated from a cost-effectiveness viewpoint through tradeoff studies which consider total system costs, including R&D, manufacturing, operation, maintenance and logistics over the life of the system.

Thus far, we have attempted to place the subject area of maintainability in a systems context. Just as reliability is a field unto itself, requiring its own specialties in terms of analysis of redundancy or quality of components and parts, maintainability has its own unique and even more diversified elements. The downtime criterion is the effect of the combined interactions of numerous discrete elements

which may be grouped under "design", "maintenance policy", or "technician requirements" as alternative means for the support of a system.

Figure 6 presents some of the variables that go into "maintainability". The problem of designing for maintainability involves weighing and evaluating the elements of what the designer controls during the design stage (e.g., module size, test and checkout alternatives) relative to the maintenance policy alternatives (echelon of repair, repair-discard) which may or may not be appropriate for the system. Additionally, as indicated in Figure 6, the design decision should be made in the manner that also fits the availability and capability of maintenance personnel as they may be allocated throughout the support system.

Relative to Figure 6, there are many tradeoffs and alternatives involved in design, maintenance policies and technician capabilities. Aside from the effect on system reliability and system availability which a design decision can have, the interrelationship among the elements making up the subject area of maintainability is such that a change in one or more will have an effect on:

1. The duration of system failure.

2. The duration of a component failure.

3. The system cost initially and over its lifetime of use.

The objective of a systems evaluation model (conceptually shown in Figure 6) is to determine the effect of the downtime of a system on system availability relative to costs. High system availability specifications in complex systems place a requirement on rapid detection to some functional level less than the system level—at a cost. Replacement of a failed module at an operational level increases system availability but raises the cost of spares. Whether to repair the component at the operational level, discard it, or ship it back for repair, requires a comparison of alternatives on the basis of cost and effectiveness. If the decision is to repair, the design of the component, the technician capability, and the echelon at which the repair is made, all influence the mean downtime (in

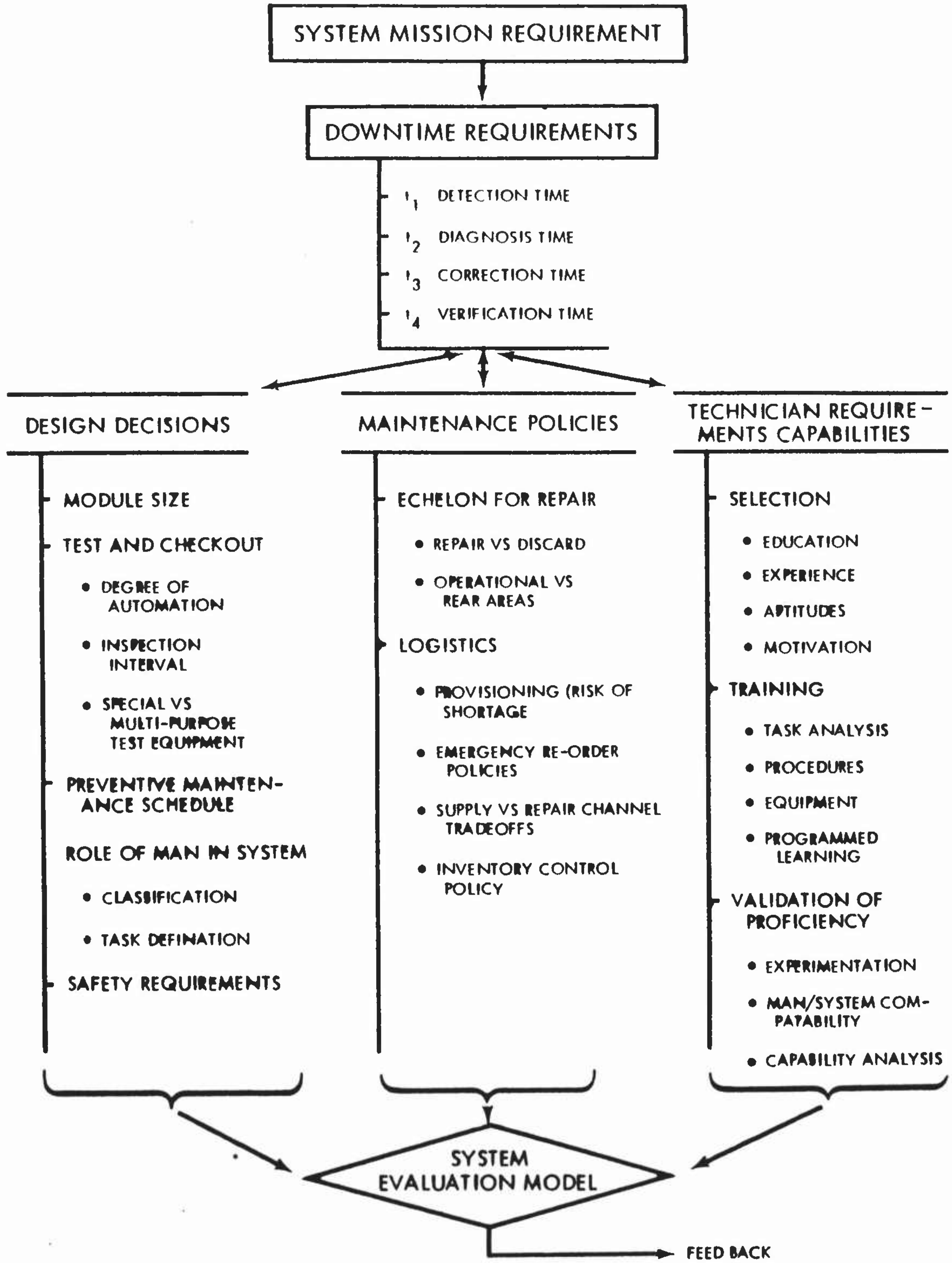

Figure 6. Typical Elements of Maintainability

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which detection and diagnosis of the failure may now be a major contributor).*

ALLOCATION OF M REQUIREMENTS

At this point we can discuss details involved in allocating system downtime requirements to the subsystem and module level, and discuss some of the intra M facets of the complex maintainability field.

Decisions as to the division of requirements among the four major elements of downtime requires detailed cost studies. If we assume that meeting system downtime requirements means that we in fact do meet specified mission requirements, then the allocation problem becomes strictly an economic one—i.e., attaining the specified downtime capability at minimum cost.

One of the primary means for reducing system downtime is to substitute automatic checkout and diagnostic equipment for the slower human operator and to use modularized, plug in components. Decisions to automate are generally made on a systems basis; the level to which automation would be carried (e.g., automatic fault isolation to a replaceable module level) would be determined by cost tradeoff studies. Results would establish consistent guide lines for allocating downtime requirements below system level to the subsystem and the component level.

The allocation procedure from this point on can best be described by a hypothetical example:

Given a system mean downtime requirement of ten minutes for failure correction and given also that no more than two maintenance actions out of a hundred should result in downtime exceeding 30 minutes. The former means we have ten minutes to be allocated among the various elements of downtime:

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* Note that downtime is of prime importance at the operational level relative to the requirements of the mission (and operational availability). Downtime in supporting echelons can generally be converted to cost by taking into account such factors as man hours, required facilities, and perhaps most important, tradeoffs between costs of items in the supply pipeline versus item downtime (i.e., extra spares are needed to support a repair cycle with low output per unit time).

Total Downtime	10 Minutes
Detection - t_1	1 minute
Diagnosis - t_2	2 minutes
Correction - t_3	6 minutes
Verification - t_4	1 minute

The most time-consuming element of downtime is generally diagnosis. However, substitution of automatic diagnostic equipment and proper selection of the module size to which the failure will be isolated can reduce this time almost to zero. The same holds true for detection and verification, depending on the extent of automation desired. This leaves the "correction" element as the one which ultimately becomes the most limiting factor in this example.

For our example, therefore, we could assign one minute for detection and two minutes for diagnosis to module level. This would leave seven minutes to be allocated between verification and corrective action. Since the same test circuitry used for "detection" could be designed to conduct automatic verification checking, we could assign one minute to the latter—leaving six minutes for taking correction action (i.e., removing module, obtaining replacement, installing the replacement).

Cost tradeoffs might indicate that it would be cheaper to go to redundant switch-in spares, thus reducing corrective time and eliminating some of the automatic checkout features. This is but one example of the many tradeoffs necessary to determine the least cost configuration.

We discussed "expected" or mean values of downtime in this example to make the point, however statistical techniques now being used in other design problems appear appropriate to handle the specified downtime distribution and variance (as well as maximum permissible downtime and percent of its occurrence.

INTRINSIC VERSUS OPERATIONAL $\underline{M}$

So far, we have been discussing the intrinsic or designed-in level of $\underline{M}$. The designer or systems engineer can be made responsible for

attaining this level. He cannot, of course, be held responsible for administrative or waiting time delays that occur during field operation. Neither can he be responsible for anticipating any unspecified environmental conditions under which the equipment might operate which would degrade performance and increase repair time.

For this reason, the system downtime requirements, as derived from mission requirements, need to be modified to provide for this less than 100 percent efficiency in the field. "K" factors must be eventually derived to permit this "derating" of downtime requirements.*

The inherent downtime capability as measured under ideal conditions in a test program would represent the maximum attainable by the equipment. The derating factor then is necessary for field use because of the environment, inefficiencies of operation, and pressures of the tactical situation.

RECAPITULATION

In this discussion we have stressed a philosophy of approach and a method for deriving certain (not all inclusive) specific maintainability design requirements. We have in particular emphasized the importance of matching M requirements to mission objectives through the connecting link of system downtime. It should be noted in closing that the approach to the M requirements problem described in this paper is just a beginning—further research is needed to become intelligent enough to translate downtime as well as other M characteristics into definitive design criteria.

A work of caution—M requirements have evolved rapidly in a matter of months from being completely non-existent to being, in some cases, elaborate detailed specifications. A serious danger exists that overspecification of details and data requirements on the part of the military customer will inhibit this necessary future research. Some of our current specifications, while performing a real advance by quantifying M—restrict the military contractor significantly in his latitude of approaches to solving the M problem.

* Research is necessary to establish values for such factors for different kinds of equipment.

It is desirable that a contractor should be asked to develop tools, such as predictive system models, early in the R&D stage of a new weapons system; it is probably not desirable to dictate detailed M data requirements and analytical techniques at this early stage. Rather the contractor should be required to meet broad system requirements, should be given maximum flexibility to do so, and should be held rigidly accountable for his final performance.

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